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APPLICATION FOR LETTERS PATENT

for

CONTOURED COMPOSITE STRUCTURAL MEMBERS AND METHODS FOR MAKING THE SAME

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CONTOURED COMPOSITE STRUCTURAL MEMBERS AND METHODS FOR MAKING THE SAME

[01] REFERENCES TO RELATED APPLICATIONS

[02] This application claims priority from U.S. provisional patent application number 60/216,636, the entire disclosure of which is incorporated herein by reference.

[03] FIELD OF THE INVENTION

[04] The present invention relates to structural members and methods for making the same. In particular, the present invention relates to contoured composite parts and methods for making the same.

[05] BACKGROUND OF THE INVENTION

[06] In recent years there has been an increasing emphasis on the use of lightweight composite materials. One application, for example, has been their use to improve the efficiency of motor vehicles. To that end, the United States Government and the U.S. Council for Automotive Research (USCAR)—which represents Daimler Chrysler, Ford, and General Motors have partnered to form the Partnership for a New Generation of Vehicles (PNGV). One goal of PNGV is to develop technology, such as composite technology, that can be used to create environmentally friendly vehicles with up to triple the fuel efficiency, while providing today's affordability, performance and safety. For example, PNGV wants to improve the fuel efficiency of today's vehicles from about 28

miles per gallon (mpg) to about 83 mpg and a 40-60% decrease in the present curb weight (3200 pounds).

[07] One method to improve the fuel efficiency is to decrease the weight of today's vehicles and use lighter weight materials. The materials used in today's vehicles, such as steel and aluminum, are quite heavy relative to composite materials, but have been necessary to provide sufficient structural properties, including tensile, compression, flexural, interlaminar shear, and in-plane shear strengths and other mechanical and material properties, to meet vehicle design requirements.

[08] Many other applications of lightweight composites have been made to supplement or replace the use of structural materials, such as steel, cast iron, and aluminum. These include buildings, bridges, recreational vehicles, aerospace, defense, and sporting goods, as well as many other applications.

[09] Composites are a mixture or combination, on a macro scale, of two or more materials that are solid in the finished state, are mutually insoluble, and differ in chemical nature. Types of composites include laminar, particle, fiber, flake, and filled composites. Composites, however, often have not had the combination of structural properties mentioned above and/or low cost necessary to promote their widespread use in motor vehicle and other applications.

[10] Despite their lack of structural strength, some composite materials have been employed in vehicle manufacturing. For example, laminated composite tubes above have been used as structural members in vehicles as well as other structures. Typically, the

tube is generally straight over its length, e.g., the radius remains constant along the length of the tube. As well, the tubes are generally circular in cross-section. See, for example, U.S. Patent Nos. 4,128,963, 4,946,721, 4,968,545, 5,061,533, Re35,081, 5,348,052, 5,447,765, 5,437,450, 5,499,661, 5,579,809, 5,624,115, and 5,725,920, the disclosures of which are incorporated herein by reference. Such structural members, however, have been typically limited to the structures described above and so their end-use and applications have been quite limited.

[11] SUMMARY OF THE INVENTION

[12] The present invention provides contoured composite structural members and methods for making the same. The contoured structural members comprise composite materials and the contoured structure can be provided by tube rolling (or roll wrapping) the composite materials together and then, if necessary, bonding them or connecting them. The outer surface of the structural member can be provided with a polygonal shape during the process of manufacturing. With a contoured structure and an outer polygonal shape, applications for the structural members of the present invention are increased.

[13] BRIEF DESCRIPTION OF THE DRAWINGS

[14] Figures 1-16 are views of structural members and methods of making the same according to the present invention. Figures 1-16 presented in conjunction with this description are views of only particular—rather than complete—portions of the structural members and methods of making the same.

[15] DETAILED DESCRIPTION OF THE INVENTION

[16] The following description provides specific details in order to provide a thorough understanding of the present invention. The skilled artisan, however, would understand that the present invention can be practiced without employing these specific details. Indeed, the present invention can be practiced by modifying the illustrated structural member and method and can be used in conjunction with apparatus and techniques conventionally used in the industry.

[17] Figure 1 illustrates one contoured structural member—a tubular member with a substantially circular cross-section—according to the present invention. In the context of the present invention, a "contoured" structural member is any shape, size, or configuration where at least one portion of the outer or inner periphery of such member is substantially non-flat, including curved, geometric or irregular. Preferably, the contoured structural members have a closed surface configuration, such as a surface that facilitates their manufacture as explained below. In the context of the present invention, a "closed" structural member is one having any shape, size, or configuration where at least one portion of the surface (inner and/or outer) of such member is a substantially closed or substantially continuous. Examples of a closed configuration include a tubular, substantially spherical, polygonal, conical, or other similar shape, as well as those illustrated and described herein.

[18] The structural members of the present invention may have a cylindrical or a non-cylindrical configuration such as cones, pyramid, pods, hemispheres or spheres. The structural members of the present invention may also have a circular or a non-circular cross-section such as rectangular, square, hexagonal, octagonal, or the like. They may also comprise very irregular, non-closed, substantially planar surfaces. Indeed, the structural members of the present invention could have any complex contoured shape or combination of contoured shapes.

[19] In Figure 1, tubular structural member 2 comprises inner section or portion 4, optional intermediate portion or section 6, outer section or portion 8, and optional core region 10. Inner portion 4, outer portion 8, and optional core region 10, can be made of any suitable composite material as described below. Core region 10 is located in an inner section of structural member 2 and, as described below, is about the size of the substrate or mandrel used in forming the structural member. Core region 10 can be of any suitable size, shape, or configuration depending primarily on the removable mandrel(s) in the manufacturing process used to make structural member 2, the configuration of structural member 2, and the desired end application of structural member 2.

[20] Core region 10 may be hollow, but may optionally be partially or completely filled with any desired core material such as foam, plastic, conducting or insulating materials, metals and/or the like. Core region 10 containing the core material may be a structural element. The core material may also be added after structural member 2 is formed, or formed integrally into the structure. If the core material is added after the formation of

structural member 2, it may be attached to structural member 2 using an adhesive or other suitable bonding means known in the art.

[21] The materials for inner section 4, optional intermediate section 6, and outer section 8 can be the same or different materials. Preferably, inner portion 4 optional intermediate portion 6, and outer portion 8 comprise the same material. In one aspect of the invention, the materials for the inner or outer portions comprise any suitable reinforced resin matrix material (RRMM), which is a resin matrix material (RMM) with continuous or discontinuous reinforcement material embedded in the resin matrix. In one aspect of the invention, the RMM is a organic resin matrix material (ORMM). See, for example, U.S. Patent No. 5,725,920 and 5,309,620, the disclosures of which are incorporated herein by reference.

[22] In one aspect of the invention, the ORMM can be a thermoset resin. Thermoset resins are polymeric materials which set irreversibly when heated. Examples of thermoset resins include epoxy, bismeleimide, polyester, phenolic, polyimide, melamine, xylene, urethane, phenolic, furan, silicone, vinyl ester, and alkyd resins, or combinations thereof. The thermoset resins can contain various additives as known in the art, such as cross-linking agents, curing agents, fillers, binders, or ultraviolet inhibitors. Preferably, epoxy, vinyl ester, or polyester resins are employed as the thermoset resin in the present invention.

[23] In another aspect of the invention, the ORMM can be a thermoplastic resin matrix material. Thermoplastic resins are polymeric materials which do not set irreversibly

when heated, e.g., they soften when exposed to heat and then return to their original condition when cooled. Examples of thermoplastic resins include polypropylene, polyethelene, polyamides (nylons), polyesters (PET, PBT), polyether ketone (PEK), polyether ether ketone(PEEK), polyphenylene sulfide (PPS), polyphenylene oxide (PPO) and its alloys, and polyvinyl resins, or combinations thereof. The thermoplastic resins can contain various additives as known in the art, such as cross-linking agents, curing agents, fillers, binders, or ultraviolet inhibitors. Preferably, polyamides (nylons), polyester, polycarbonate and polypropylene resins are employed as the thermoplastic resin in the present invention.

[24] The material used to reinforce the RMM of the present invention can be in any form which reinforces the resin matrix. Examples of reinforcement forms include unidirectional tape, multidirectional tapes, woven fabrics, roving fabrics, matt fabrics, preforms, fibers, filaments, whiskers, and combinations thereof. The type of material used to reinforce the RMM can be any type serving such a reinforcing function. Preferably, the form of the reinforcement materials for the resin matrix is a fiberous material, such as continuous or discontinuous fibers. Examples of materials that can be employed in the present invention include glass-s, glass-e, aramid, graphite, carbon, ultra-high molecular weight polyethylene, boron, silicon carbide, ceramic, quartz, metals, isotropic metals (aluminum, magnesium and titanium), metal coated organic fibers, CAMP, hybrids of these fibers, or combinations of these fibers. See, for example, U.S. Patent No. 6,117,534, the disclosure of which is incorporated herein by reference.

[25] In yet another aspect of the invention, non- or partially-cured composite materials are used as the material for the inner and/or outer sections. Composites are a mixture or combination, on a macro scale, of two or more materials that are solid in the finished state, are mutually insoluble, and differ in chemical nature. Any composites known in the art such as laminar, particle, fiber, flake, and filled composites can be employed in the invention. The non- or partially-cured composite materials are a ORMM (thermoset or thermoplastic resin) reinforced with a continuous fiber.

[26] Preferable composite materials used for inner section 4 and outer section 8 include B-stage prepreg materials typically in the form of sheets or laminates, which can be formed by impregnating a plurality of fiber reinforcement tows with a formulated resin. Methods of making B-stage prepreg sheets and the sheets themselves are well known. See, for example, those sheets described in U.S. Patent No. 4,495,017, the disclosure of which is incorporated herein by reference. When cured, prepreg materials are generally stronger and stiffer than metals while providing greater resistance to fatigue, chemicals, wear and corrosion. Preferable reinforcement for prepregs include aramids, glass materials, nickel carbide, silicone carbide, ceramic, carbons and ultra-high molecular weight polyethylene, or a combination thereof. See, for example, U.S. Patent Nos. 4,968,545, 5,102,723, 5,499,661, 5,579,609, and 5,725,920, the disclosures of which are incorporated herein by reference. Carbon, glass, metals and especially isotropic metals like aluminum, magnesium and titanium, metal-coated organic fibers, and aramid fibers, or a combination thereof, can also be employed as the fibers. See, for example, U.S.

Patent Nos. 5,601,892 and 5,624,115, the disclosures of which are incorporated herein by reference. Preferably, carbon fibers, glass fibers, or aramid fibers and more preferably Kevlar 29 or 49 fibers are employed in the present invention.

[27] The fiber volume in the prepregs may be varied so as to maximize the mechanical, electrical, and thermal properties. See, for example, U.S. Patent No. 5,848,767, the disclosure of which is incorporated herein by reference. High fiber volume parts are stiffer and, in the case of thermally conductive fibers, the parts are more thermally conductive. Fiber volumes in the present invention can range from about 5% to about 95%, and preferably range from about 50% to about 65%. The fibers of the prepregs may be oriented within the prepreg material in any desired direction as known in the art, such as about 0 to about 90 degrees, including equal numbers of fibers balanced in opposing directions. See, for example, U.S. Patent No. 4,946,721, the disclosure of which is incorporated herein by reference.

[28] In yet another aspect of the invention, sheet molding compounds (SMCs) can be used as the materials for the inner or outer portion. SMCs are sheets made up of B-stage thermoset resin reinforced with a discontinuous fiber. SMCs are fully formulated ORMM compounds having discontinuous fiber reinforcement materials which are typically formed into sheet, ply, or laminate—without additional preparation. See, for example, U.S. Patent No. 6,103,032, the disclosure of which is incorporated herein by reference. The resins that can be used in the SMCs of the present invention include any of the thermoset resins listed above. Preferably, polyester vinyl esters or epoxy resins are

employed as the resin in SMCs of the present invention. The fibers that can be used in the SMCs of the present invention include any of those listed above. Preferably, glass, carbon, or aramid fibers, and more preferably Kevlar 29 or 49 fibers can be used as the fibers in the SMCs. The fiber volume in the SMC may also be varied so as to maximize the mechanical and thermal properties.

[29] With an unsaturated resin system as its base, SMCs incorporate other materials for desirable processing and molding characteristics and optimum physical and mechanical properties, such as mechanical strength, impact resistance, stiffness, and dimensional stability. These incorporated materials include polymers, fibers for reinforcement, resins, fillers, initiators to promote polymerization, viscosity agents, lubricants, mold release agents, catalysts, thickeners, pigments, polyethylene powders, flame retardants, ultraviolet absorbing agents, and other additives. Each of the additives can provide important properties to the SMC, either during the processing or molding steps or in the finished parts, and can be incorporated in the SMCs of the present invention.

[30] In one aspect of the invention, inner section 4, optional intermediate section 6, and outer section 8 contain at least one layer of such ORMM materials. One layer is sufficient to form the respective inner or outer section and provide the desired structural characteristics for structural member 2. Additional layers can be added to improve the strength, stiffness, or other physical characteristics of structural member 2. It is possible to use a single layer with fibers having complementary orientations. It is preferred, however, to use a plurality of layers with complementary orientations to balance intrinsic

stresses in the layers that make up the sections that result when, as described below, the B-stage materials are fully cured. To be complementary, the fibers in successive layers should be symmetric and balanced (e.g., by having the fibers offset from the sheet axis by equal and opposite amounts from one layer to another) as shown in Figure 2. The fibers can also be oriented to meet the design parameters of the component into which they are being incorporated, e.g., to optimize the structural strength against the expected load. The fibers could be oriented at any suitable angle, including at angles ranging from about 0 to about 90 degrees, including in ±15, ±30, ±45, ±60, and ±75 degrees, or as otherwise known in the art. See, for example, U.S. Patent Nos. Re. 35,081 and 5,061,583, the disclosures of which are incorporated herein by reference.

[31] The configuration of inner portion 4 optional intermediate section 6, and outer portion 8 can vary within structural member 2. For example, the materials used for the composite, the fiber orientation, and the curvature, thickness, shape and other characteristics of the inner and/or outer portions (4, 8) can differ along the length and width of structural member 2. See, for example, U.S. Patent No. 5,718,212, the disclosure of which is incorporated by reference.

[32] The structural member of the present invention may, if desired, have additional layers or portions on the outside of outer portion 8. In one example, a layer of metal, insulation, another composite material, or honeycomb core material may be placed over outer portion 8. Numerous additional portions or layers, including similar or different composite materials, could be added in a similar manner. In addition, at least one

structural component, such as a bracket, coupler, cap, or the like could be located on the end(s) of structural member 2.

[33] The structural member of the present invention may have any substantially non-flat contour or configuration. Figure 4 illustrates several such configurations. In one aspect of the invention, the structural members of the present invention can be configured with any contoured shape known in the art. The contoured shapes can have any combination of inner or outer shapes, inner and outer thickness, and inner or outer radii.

[34] In preferred aspect of the invention, the structural members of the present invention have the contoured shapes illustrated in Figure 12. The preferred contoured shapes have a thickness and/or a radius that varies—either regularly or irregularly—along the length of the structural member. For example, referring to Figure 12, the structural member 2 comprises a first portion 41 with a first diameter, a second portion 42 with a second diameter, and a third portion 43 with a third diameter. As another example, as illustrated in Figure 13, the structural member 2 comprises a first portion 46 with a first thickness, a second portion 47 with a second thickness, and a third portion 48 with a third thickness.

[35] In another preferred aspect of the invention, the shape of the structural member has a shape other than substantially circular. Examples of such shapes include rectangular, hexagonal, octagonal, polygonal, etc… Making the tube with polygonal shape—such as a hexagon—provides several flat surfaces on the inner or outer surface of the structural member, which becomes important when bonding the surface of the

structural member to another member, such as a metal end piece. An interference is created between the surface of the other member (metal end piece) and the surface of the structural member, supplying torsional resistance when either the structural member or the end piece is subjected to a load. The larger the interference, the more resistance is given to the torsion, separate from the resistance provided by the bond surface. The amount of interference is proportional to the torsional resistance, so increasing the diameter or decrease the number of polygon flats thereby increases the resistance to torsion, as is depicted in Figure 14.

[36] Creating a polygonal shape, however, creates a secondary loading condition on the structural member. This loading condition is usually localized near the bond surface and can easily be great enough to explode the structural member from the inside. To protect against such a problem, that area of the structural member 2 is "overwrapped" with a composite collar comprising of fibers which are oriented around the circumference of the structural member. This prevents the structural member from exploding, while not adding much weight. The overwrap is located over the entire joint area with some extension past the joint to help with stress concentrations.

[37] The optimum number of sides of the polygonal shape depends on the individual design. The more sides used, the less interference there will be and the less torsional resistance. Yet increasing the number of polygonal sides moves closer to a round shape. So reducing the optimum joint strength to weight ratio will also increase the optimum tube strength to weight ratio. The number of composite plies used in the overwrap also

depends on the design and the internal pressure due to the torsion and the resistance to internal pressure. Obviously a thicker tube would normally resist more internal pressure and require less number of overwrap plies. But then it may have a significantly larger internal pressure due to a large torsional load. As with every design, the optimum design will be the one which is the lightest for it's given strength and stiffness.

[38] The structural members of the present invention can be made by any suitable process that provides the desired structure. Suitable process for making the composite layer(s) include any processes known in the art, such as thermoforming, bladder or resin transfer molding, or inflatable mandrel processes, as described in U.S. Patent Nos. 5,225,016, 5,192,384, 5,569,508, 4,365,952, 5,225,016, 5,624,519, 5,567,499, and 5,851,336, the disclosures of which are incorporated herein by reference. Another suitable process is a vacuum bagging process, such as described in U.S. Patent No. 5,848,767, the disclosure of which is incorporated herein by reference. Other suitable processes are a filament winding process or sheet or tube rolling (also known as roll wrapping). See, for example, U.S. Patent Nos. 5,632,940, 5,437,450, 4,365,952, 5,624,529, 5,755,558, 4,885,865, 5,332,606, 5,540,877, 5,840,347, and 5,914,163, the disclosures of which are incorporated herein by reference.

[39] In the filament winding process, filaments of the desired material are dispersed in a matrix of binder material and wound about any suitable substrate, such as a mandrel assembly. Any suitable mandrel or mandrel assembly, including those described in U.S. Patent Nos. 5,795,524, 5,645,668, 5,192,384, 5,780,075, 5,632,940, 5,817,203, and

5,914,163, the disclosures of which are incorporated by reference, can be employed in the present invention.

[40] In one aspect of the invention, the substrate or mandrel must have sufficient strength, desired shape, and be able to withstand the processing conditions for making the structural member. Suitable mandrels include those made of metals like steel and aluminum, polycarbonate, thermoplastic, or RRMM materials. The mandrels may be solid or hollow. The mandrel or substrate should have a shape generally corresponding to the desired shape (core region 10) of structural member 2, e.g., the outer surface of the mandrel should have a shape corresponding to the inner surface of the inner portion 4.

[41] The filaments are wound over the mandrel and are reciprocally displaced relative to the mandrel along the longitudinal or winding axis of the mandrel to build portion 4. Additional portions, structures, or layers, such as additional metal or composite layers, can be added as described above or as known in the art.

[42] Preferably, the present invention employs a tube rolling (also known as roll wrapping) process for making the structural member of the present invention. One exemplary tube rolling process is illustrated in Figure 5. The tube rolling process employs discrete sheet(s) (or plies or laminates) of the desired composite material rather than filaments. The sheet(s) is interleaved, wrapped, or rolled over a mandrel assembly such as at least one mandrel 20. If desired, a release film can be applied to the mandrel prior to rolling any materials thereon. When more than one sheet is employed, the sheets can be stacked as illustrated in Figure 2—prior to or during the rolling process—by hand

or by any suitable mechanical apparatus, with the fibers of the composite material oriented in the desired orientation. After forming inner portion 4, the roll wrapping process continues to apply the material of outer portion 8. Further details about roll wrapping processes are described in *Engineered Materials Handbook, Volume 1: Composites*, ASM International, pp. 569-574 (1987), the disclosure of which is incorporated herein by reference.

[43] Additional layers or materials can be added over outer portion 8, if desired, in a similar manner using any of the above processes. By adding additional composite plies or additional composite materials at this stage, the structural members illustrated in Figures 12 and 13 can be created. For example, the "base" structural member illustrated in Figure 13, can be made by the above process. Then, additional plies (or sheets) of the desired material can be added by wrapping in the desired areas to obtain the varying the additional thicknesses. In a similar manner, additional plies can be wrapped to create the overwrap described above.

[44] The layers of the individual portions (inner, intermediate, and outer) can be cut and/or patterned such that when roll wrapped, the ends of individual sheet(s) substantially abut when rolled, thereby forming a butt joint 30. Preferably, the butt joint formed by the ends of any single sheet is staggered from the butt joint formed by the ends of an adjacent sheet, as illustrated in Figure 6.

[45] Inner portion 4 and outer portion 8 may be formed using different methods. For example, inner portion 4 can be formed by filament winding and outer portion 8 by roll

wrapping, or vice versa. In this aspect of the invention, inner portion 4 may be fully cured prior to the application of intermediate portion 6. Similarly, inner portion 4 and intermediate portion 6 may be applied and cured together prior to the application of outer portion 8. Other methods known in the art, such as those described above, could also be combined with roll wrapping to make the structural members by performing discrete steps by different methods. For example, inner portion 4 could be formed using the filament winding process, intermediate portion 6 and outer portion 8 could be formed using the roll wrapping process, and then this intermediate structure could be constrained using a vacuum bagging process.

[46] If desired, a bonding agent can be placed between successive layers of portions 4 and/or 8. The bonding agent can be placed on selected areas only, or in a pattern such as in rows and/or columns, or over entire areas of the layer(s)/portion(s). Any suitable agent which helps bond the layers and is compatible with all of the processes employed to make structural member 2 can be employed, including glues, curing agents, adhesive materials, or a combination thereof. See, for example, U.S. Patent No. 5,635,306, the disclosure of which is incorporated herein by reference. The bonding agent can be applied by hand or mechanical apparatus prior to, during, or after the assembly of the respective portion on the substrate.

[47] Where portions 4 and 8 are successively layed up in an uncured (e.g. B-stage state), the structure has outer portion 8 overlying inner portion 4, which overlies the mandrel. If necessary to better bond and connect inner portion 4 and outer portion 8

together, the intermediate structure formed by these portions can be constrained. The intermediate structure can be constrained by applying a suitable compressive force. This can be done using any suitable means including compressive dies or molds, vacuum bagging, or by using a suitable constraining means, e.g., by placing it in a plastic or metal mold, or by applying a suitable shrink-wrap tape(s) 22 or tube made of nylon, silicone, or polypropylene. During the curing process described below, the compressive means (e.g., the shrink-wrap tape or tube) applies suitable compressive force by physical or chemical change so that the materials of structural member 2 contact each other. When the RMM is used in the inner and/or outer portion of the present invention, the compressive force squeezes out excess resin during this curing process. See, for example, U.S. Patent Nos. 5,600,912 and 5,698,055, the disclosures of which are incorporated herein by reference.

[48] Moreover, if it is still necessary to better bond and connect the materials in the intermediate structure, they can undergo a suitable chemical reaction. For example, when inner portion 4 and/or outer portion 8 comprise a curable material (e.g., B-stage epoxy prepreg), the intermediate structure can be cured by any suitable means 24, such as an oven curing by applying heat and/or pressure or using an ultraviolet (u.v.) or microwave curing. The necessary heat and/or pressure depend on the size of the mandrel assembly and the materials used in structural member 2. During the curing process, the shrink-wrap tape or tube applies suitable compressive force. When the RMM is used in the inner and/or outer portion of the present invention, the compressive force squeezes out excess resin during this curing process.

[49] The above process can be modified for structural members not having a substantially circular cross-section, including those with outer diameters having at least one flat area or area where the degree of curvature is substantially different from other surfaces of structural member 2. Examples of such structural members are illustrated in Figure 4. As illustrated in Figure 7, where the outer diameter has at least one relatively flat area, the shrink-wrap material (and accompanying compressive force) applied to the intermediate structure may not be uniform. Thus, bonding and connecting the materials to one another may not be uniform and, therefore, might impair the integrity of structural member 2. To more uniformly bond and connect such materials, at least one pressure distributor 26 is placed over the relatively flat areas of outer portion 8 prior to applying the shrink-wrap material. The pressure distributors "distribute" the applied compressive force more evenly to such flat areas, allowing a more uniform compressive force to all areas of the intermediate structure.

[50] Any suitable shape of pressure distributors which evenly distribute the applied compressive force to the intermediate structure can be employed in the present invention. Exemplary shapes of the pressure distributors include substantially semicircular shapes (which provide a substantially circular outer surface) and T-shaped distributors where the flat end of the "T" abuts (and matches in size) the flat area of the intermediate structure and the long-end of the "T" extends outwards. Other shapes and configurations, including single components rather than plural components, could be employed provided they evenly distribute the compressive force over the flat area(s). For the structural

member 2 like the one illustrated in Figure 4, substantially semicircular pressure distributors 26 are depicted in Figure 7. The pressure distributors of the present invention can be made of any suitable material that will maintain its shape when subjected to the compressive force, such as aluminum, steel, and silicone. Preferably, aluminum is employed as the material for the pressure distributor.

[51] The shrink-wrap material can be placed under and/or over the pressure distributor(s). The shrink-wrap materials underlying the pressure distributors pressurize the corners, as well as keeping the pressure distributors from sticking to the intermediate structure. The shrink-wrap materials overlying the pressure distributors pressurize the flat areas.

[52] The above process can be also be modified for structural members where the inner and outer portion do not have the same shape, such as those depicted in Figure 11. Any suitable process modification which manufactures differently-shaped inner and outer portions can be employed in the present invention. The following two modifications to the above process demonstrate this concept. Other modifications could be envisioned, even though not demonstrated below.

[53] First, the inner portion can have a substantially circular cross-section and the outer portion a non-circular cross-section. In such an instance, and as shown in Figure 8, the process for making a circular-shaped structural member is followed as described above. To change the shape of the outer portion, a number of pressure distributors are placed over the circular-shaped outer portion prior to the constraining and curing stages. The

number of pressure distributors used corresponds to the number of flat sides desired, e.g., four for a square, six for a hexagon, etc... The process as noted above is then continued for the constraining and curing stages. During the constraining and curing process, the circular outer shape is changed to flat sides of the desired polygonal shape by the pressure exerted via the pressure distributors.

[54] Second, the inner portion can have a substantially polygonal shape (i.e, hexagon) and the outer portion a substantially circular shape. In this aspect of the invention as depicted in Figure 9, the process for making a hexagonal-shaped structural member is followed as described above. To change the shape of the outer portion, the pressure distributors that are normally placed over the outer portion prior to the constraining and curing stages are omitted. Thus, the square-shaped outer portion is just wrapped with the constraining means. The process as noted above is then continued for the constraining and curing stages. During the constraining and curing process, the outer shape is changed to a substantially circular shape by the pressure exerted via the constraining means.

[55] When used, the constraining means are then removed from the intermediate structure. For the plastic or metal mold, the mold is opened and removed. The shrink-wrap tape or tube may have reacted during the curing process to form a thin shell and, if desired, may be removed by hand or by a mechanical apparatus. When used, the pressure distributors are also removed.

[56] In another aspect of the invention, the constraining means can be left on the outer portion either temporarily or permanently. For example, the shrink-wrap tape could be

left on the structural member in the form as a thin shell for protection during shipping and then removed later. In another example, the shrink-wrap tape could be left on the structural member permanently as a protective coating.

[57] Through the constraining and curing processes described above, the inner portion and the outer portion are chemically attached and/or or connected to the intermediate portion. Preferably, the materials of the inner and outer portion both chemically bond to the material of the intermediate portion, thus forming a substantially permanent physical bond.

[58] Next, the substrate or mandrel may be removed from structural member 2 to form core region 10. The mandrel may be removed by any suitable process, including any known in the art which safely removes the mandrel without adversely impacting structural member 2, such as those disclosed in U.S. Patent No. 5,900,194 and 5,306,371, the disclosures of which are incorporated herein by reference. If desired, core region 10 can be filled by any desired material as known in the art.

[59] The mandrel can be either a removable mandrel or an integral mandrel. A removable mandrel is a mandrel that, as described above, is used in the roll wrapping process and then removed to create interior 10. An integral mandrel is a mandrel which becomes part of structural member 2 and is not removed. Thus, the mandrel remains in core region 10 and becomes a part of structural member 2.

[60] When using an integral mandrel, the structural member 2 and the process for making that member are modified from the above description. In this aspect of the

present invention, the intermediate portion is provided over the integral mandrel, and then the outer portion is provided over the intermediate portion. The structural member then follows the processing described above, with the exception that the integral mandrel is not removed. Thus, the integral mandrel can serve as the inner portion. If desired, an inner portion could still be included over the integral mandrel, yielding a structural member with an integral mandrel, an inner portion, an intermediate portion, and an outer portion.

[61] Once formed, the structural members of the present invention can be modified or cut for any desired use. For example, the structural members illustrated in Figures 5 and 7-9 have been cut in half along its length to provide two structural members. Likewise, the structural members could be cut along its length to provide any number of members with the desired length(s). Numerous shapes and configurations can be made using by cutting along any dimension of the structural members, especially when combined with the broadest aspects of the processes of the present invention. A few examples of the shapes and configurations obtained by cutting the structural members in the above manner are shown in Figure 10.

[62] In a preferred aspect of the invention, and as illustrated in Figure 15, selected portions of the outer portion 8 are provided with an overwrap 6. The overwrap can be provided by any means known in the art. Preferably, the overwrap is provided by selecting the desired size (and thickness) of the plies 50 needed to form the overwrap and then roll wrapping these plies 50 over the selected portions of the outer portion 8. The

structural member can then be cut radially in the middle of the overwrap, thereby providing two or more structural members with overwrapped portions on one—or both—of their ends.

[63] After cutting the structural members of the present invention, additional structural components can be added. Any structural component known in the art can be added to the modified structural member, such as a bracket, fastener, coupler, cap, or the like. In a preferred aspect of the invention, the structural members have a metal end piece bonded in an the end thereof, thereby creating a structural part for torque type application which can be used as a drive shaft, half shaft, or likewise.

[64] Further modifications—other than just cutting—can be made to the structural members of the present invention. For example, channels, holes, patterns, and similar modifications can be made in the inner or outer surface of the structural member for many reasons, such as to attach a structural component, modify the surface properties, or a similar purpose.

[65] Roll wrapping is the preferred method for making the structural members of the present invention. The other methods described above, however, could be combined with roll wrapping to make the structural members by, in one aspect of the invention, performing discrete steps by different methods. For example, inner portion 4 could be formed using the filament winding process, the intermediate portion 6 and the outer portion 8 could be formed using the roll wrapping process, and then the intermediate structure could be constrained using the vacuum bagging process.

[66] The structural member of the present invention has numerous uses such as a tie, torsion-bar, tube, beam, column, cylinder and the like and can be used in numerous industries. Primarily, the structural member can be used whenever a lightweight, strong, cylindrical object is required. The structural member of the present invention can be used in the automotive, transportation, aerospace, and defense industries in applications such as airplane components, vehicle components such as tracks, trains, shipping containers, defense-related applications, recreational applications such as bikes, sail masts, shafts for golf clubs and racquets, or commercial applications such as bridges and buildings. The following non-limiting examples illustrate the present invention.

[67] Example 1

[68] A hollow, cylindrical structural member with a circular cross-section outside and hexagonal inside was made according to following process. A thin coat of a release material (Frekote 700NC or Axel EM606SL/SP) was applied to a 0.3125" radius hexagonal aluminum mandrel with six equilateral outer sides of 0.3125 inch and a length of 56 inches.

[69] Nine pairs of B-stage prepreg laminate sheets (18 individual sheets) containing anisotropic carbon fibers were cut to a length of about 2.25 to about 2.84 inches in width and about 52 inches in length. The sheets each have different widths according to their location in the lay-up on the mandrel, e.g., each layer sufficiently wide to form closely-spaced butt joints when the layer is wrapped around the mandrel. The individual laminate sheets were then overlaid so the fibers in successive sheets were symmetric and

balanced at angles of ±45 degrees. The air between the stacked sheets was removed by using a roller or other suitable device. The stacked prepreg sheets were then roll wrapped by hand around the aluminum mandrel with a butt joint.

[70] A first set of two strips of unidirectional tape containing anisotropic carbon fibers were cut to a length of about 10 inches and about 1 inch in width. A second set of two more strips of unidirectional tape containing anisotropic carbon fibers were cut to a length of about 10 inches and about 2 inches in width. The first set of strips were wrapped on the prepreg sheets to create an outer set of overwraps, leaving about 0.5 inch from each end without any overwrap (e.g., the middle of the overwrap is located 1 inch from the end). Similarly, the second set of strips were wrapped on the prepreg sheets to create an inner set of overwraps located so the middle of the overwrap is about 17.5" from the ends. Given the length of the overwraps and the outer circumference of the prepreg layers on the mandrel, both the inner and outer sets of overwrap contained five layers.

[71] Next, the resulting intermediate structure was shrink-wrapped. One layer of polyethylene-based shrink-wrap tape was roll wrapped by a shrink-wrapping machine using gauge number 150 on the resulting structure. Another layer of nylon-based shrink-wrap tape was then roll wrapped by a shrink-wrapping machine using gauge number 200.

[72] After this wrapping process, the final structure was subjected to a curing process at about 250 degrees Fahrenheit for about 120 minutes during which the shrink-wrap tapes applied compressive pressure to the intermediate structure. After this curing process, the shell (formed by the shrink-wrap tapes during the curing process) was

removed by hand with a knife. The mandrel was then removed from the center of the tube by hand.

[73] The half-inch section from each end (with no overwrap) of the resulting structural member was cut off and discarded. The rest of the tube was cut into three, substantially equal 17-inch sections with about a 1" wide overwrap on each end using 0.125 inch thick diamond saw. Thus, three 17" torque tubes were created with the following characteristics: a hexagonal inside and circular outside cross-section, 18 composite layers (or sheets), and 1 inch overwraps at each end containing 5 composite layers (or sheets).

[74] Similar torque tubes were then created. A first group of torque tubes were created similar to the above process, but having 10, 12, 14, and 16 composite sheets instead of 18 composite sheets. A second group of torque tubes were created similar to the above process, but having 3, 10, and 15 composite layers in the overwraps instead of the 5 composite slayers.

[75] The torque tubes were subjected to the following torque test. First, a solid equilateral hexagonal low carbon steel shaft with about 0.312" sides was cut into one-inch long sections. Half of section was cleaned with acetone to remove any oil and other contaminants, sand blasted, and then cleaned again with acetone. The clean section of a steel shaft was then bonded to a torque tube using Hysol EA 9430 adhesive, leaving about 0.5 inch section of the steel shaft exposed. The torque tubes (with inserted steel shaft) were then oven cured for one hour at 200 °F. The torque tubes with the inserted steel shaft were tested at room temperature using CDI Torque Wrench (Model Number 6004

CFII). The torque wrench records only maximum torque between 60 and 600 Ft-Lbs, with an accuracy of +/- 1%.

[76] The test results are reported in Figure 16. The results indicated that the steel shaft broke at different points depending on the number of composite layers in the tube and the number of composite layers in the overwrap. Although not reflected in Table 1, generally the torque of any composite shaft depended on the type of materials used, the radius of tube, polygon shape and size, the number of layers in the composite tube, the configuration of composite layup, and the number of overwrap layers.

[77] Having described the preferred embodiments of the present invention, it is understood that the invention defined by the appended claims is not to be limited by particular details set forth in the above description, as many apparent variations thereof are possible without departing from the spirit or scope thereof.